

# Anomalous proximity effect in mesoscopic normal-metal–superconductor structures

V. N. Antonov

*NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi-Shi, Kanagawa 243-01, Japan*

A. F. Volkov

*Institute of Radioengineering and Electronics RAS, Mokhovaya 11, Moscow 103907, Russia*

Hideaki Takayanagi

*NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi-Shi, Kanagawa 243-01, Japan*

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Anomalous corrections to the resistance have been found in mesoscopic normal-metal–superconductor (NS) structures below  $T_C$ . They differ from those described by the classical “proximity” theory in sensitivity to magnetic field, temperature, and rf irradiation. Contrary to the case of the classical proximity effect the anomalous corrections can be both positive and negative. A possible model which describes the anomalous corrections reported here is discussed. [S0163-1829(97)01606-8]

## INTRODUCTION

A new field of solid-state physics, the transport properties of mesoscopic normal-metal–superconductor (NS) structures, has attracted a great deal of attention in recent years. In nanometer scale samples a number of novel effects have been predicted (see, for example, Ref. 1 and references therein). The interference phenomena in the so-called Andreev interferometer is an intriguing example of the behavior in such systems. The effect manifests itself in a normal conductor in contact with two superconductors as resistance oscillations, when the phase difference between the superconductors is changed.<sup>2–5</sup> The classical “proximity” theory, which takes into account the penetration of the superconducting condensate function in the normal conductor, has been proposed to explain the phenomena.<sup>1</sup> In most cases the experimental data were in agreement with theory, however, in some experiments behavior, which cannot be explained within the framework of the classical proximity theory, has been observed. Thus the resistance of the normal conductor had anomalous temperature and magnetic-field dependencies, and even increased below  $T_C$  of the superconductor.<sup>3</sup> So far these effects have not received much attraction because of a lack of convincing experimental data and a reasonable theoretical explanation. Our aim is to study and clarify the nature of these anomalous proximity effects in mesoscopic NS structures.

We examined short silver wires in contact with a superconducting aluminum film. Their transport properties were studied as a function of temperature, magnetic-field, and rf irradiation. We found two types of superconductor-induced corrections to the resistance of the normal wires. The correction of the first type manifested itself as a gradual decrease of the wire resistance below  $T_C$  for aluminum. The amplitude of the effect was 0.5–10 % of the normal resistance at  $T=0.35$  K. In samples with an Andreev interferometer geometry this correction displayed a sensitivity to the phase of the superconductor. The applied magnetic field and rf radiation suppressed the effect gradually. The second, anomalous

correction, appeared as a steplike change in the resistance at the onset of the superconducting transition. A correction of this type had both positive and negative signs in different samples. The change in resistance was up to 10% of the normal-state resistance. Decreasing the temperature did not change the amplitude of the effect. An applied magnetic field suppressed the correction in a steplike manner, while a sensitivity to rf irradiation was not found. Classical proximity theory gives an accurate explanation of the first type of correction. The nature of the second type, anomalous corrections, is still unclear.

## EXPERIMENT

A plan view of experimental structures is presented in Fig. 1. Two silver wires, (i) and (ii), share the same loop at the stubs. The loop is composed of three aluminum and one silver branches. The samples have been defined using two successive electron-beam lithography steps. The NS contacts occur at the overlap of the aluminum and silver film. To ensure a good contact between the films, we cleaned the silver surface in an argon plasma just before the evaporation

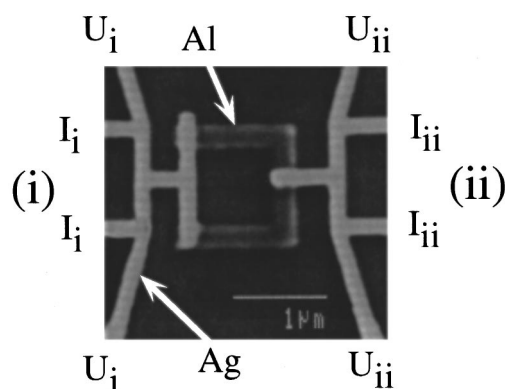


FIG. 1. SEM picture of the structures studied. The resistance of the Ag wires was measured by a four-point method.  $I$ - $I$  and  $U$ - $U$  denote current and potential leads for the measurement.

of the aluminum. A typical resistance of a NS contact was  $1\text{--}2\Omega$ . The value was extracted from  $I$ - $V$  characteristics measured across the loop ( $I_i$ - $I_{ii}$  were used as the current leads and  $U_i$ - $U_{ii}$  as the potential leads). The parameters of the silver wires were as follows: width  $w \approx 150$  nm, thickness  $d \approx 40$  nm, sheet resistance  $R_{\text{sheet}} \approx 0.35\Omega$ . The phase-breaking length, estimated from the weak localization magnetoresistance of coevaporated silver film, was  $\sim 1$   $\mu\text{m}$  at  $T=0.35$  K. The aluminum film had a thickness 40 nm and transition temperature near 1.5 K.

The measurements were performed in a shielded  $\text{He}^3$  refrigerator in the temperature range from 0.3 to 1 K. We studied the variations of the silver wire resistance as a function of temperature, perpendicular magnetic field, and rf radiation. A lock-in technique with a low-frequency,  $f=87$  Hz, probe current was used to measure the resistance. The current and potential leads are identified in Fig. 1. One can see that the NS contacts were out of the classical current paths. A typical value of the probe current was 1  $\mu\text{A}$ . rf irradiation in the 1–16 GHz range was supplied from the top of the refrigerator to the sample by a coaxial cable and coupled to the structure capacitively.

At the onset of the superconducting transition the resistances of both silver wires, (i) and (ii), were reduced. The resistance of the type (ii) wire decreased gradually with the temperature, while for the type (i) wire the gradual decrease was preceded by a steplike drop. During subsequent cooling the resistance trends of both wires were identical: the resistances gradually decreased. The total effect at  $T=0.35$  K reached 0.5–10 % of the normal resistance. An unusual behavior, a steplike drop of the resistance, persuaded us that in type (i) wire together with the well-known proximity correction to the resistance displaying as a gradual decrease of the resistance below  $T_C$ , there was another one, which we referred as an anomalous correction.

Experiments with a magnetic field also revealed two types of corrections to the resistance, see Fig. 2(a). The magnetoresistance of the type (ii) wire exhibited a gradual increase with saturation at  $H=250$  G, where the correction to the resistance was totally suppressed. In the wire of type (i) the periodic oscillations were superimposed on a monotonous growth. The period of the oscillations corresponded to the flux quantum  $\Phi_0$  through the area of the loop,  $S_{\text{loop}} \approx 1.2$   $\mu\text{m}^2$  ( $S_{\text{loop}}$  was defined by the center lines of the conductors composing the loop). At  $H=130$  G an anomalous steplike transition took place. The oscillations continued after the transition, preserving the phase.

To ensure that the steplike behavior is not a simple suppression of the order parameter in Al by the magnetic field, we measured the magnetoresistance across the loop, curve (i)&(ii) in Fig. 2(a). For this measurements ( $U_i, U_{ii}$ ) and ( $I_i, I_{ii}$ ) were used, respectively, as potential and current leads, see Fig. 1. With such an experimental scheme the aluminum branches of the loop, together with NS interfaces and normal wires, are included in the measurement. One can see that the superconducting transition of the aluminum takes place at  $H=240$  G, and no features of the magnetoresistance curve are visible near  $H=130$  G.

The steplike behavior was not unique to type (i) wire. An analogous effect has been found in type (ii) wires in some samples, while the resistance of type (i) wires exhibited no

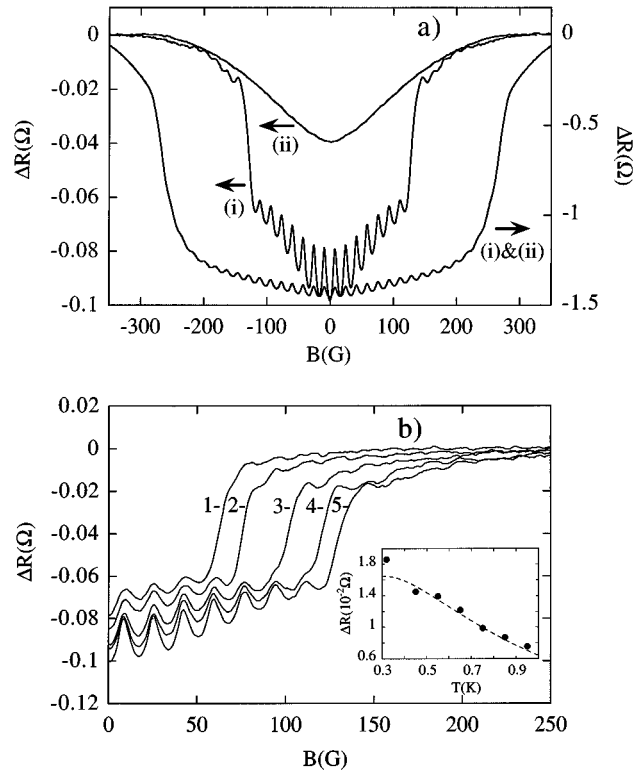


FIG. 2. (a) Magnetoresistance curves for the type (i) and type (ii) wires shown in Fig. 1. The curve labeled (i)&(ii) corresponds to the measurement across the loop, using  $U_i$ - $U_{ii}$  as potential leads and  $I_i$ - $I_{ii}$  as current leads, see Fig. 1. The data were taken at  $T=0.35$  K; (b) magnetoresistance curves for the type (i) wire at different temperatures: (1) 0.95 K, (2) 0.85 K, (3) 0.65 K, (4) 0.45 K, (5) 0.32 K; inset: experimental, filled circles, and theoretical, dashed line, temperature dependencies of the amplitude of first oscillation.

steplike transitions. An anomalous proximity effect has also been observed in samples with different geometries. The steplike corrections to the resistance had both positive and negative signs. We present magnetoresistance curves for a sample with a positive correction in Fig. 3. One can see that gentle increase in the resistance occurs before a steplike drop

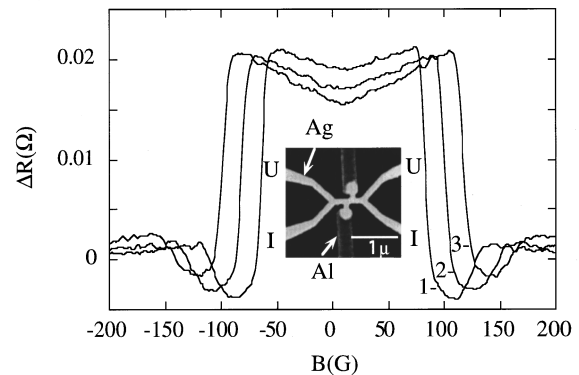


FIG. 3. Magnetoresistance curves of the structure with a positive anomalous correction to the resistance at different temperatures: (1) 0.75 K, (2) 0.55 K, (3) 0.33 K. Inset: SEM picture of the structure and four-point measurement configuration.

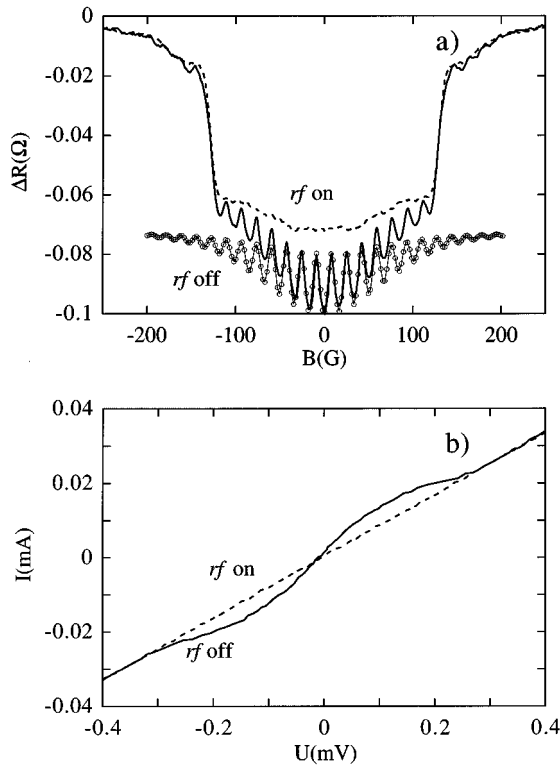


FIG. 4. (a) Magnetoresistance curves for the type (i) wire with the rf irradiation of  $f=2.043$  GHz and without rf irradiation at  $T=0.35$  K. The curve indicated by open circles is the approximation derived from the classical “proximity” theory, see the details in the text; (b)  $I$ - $V$  curves across the loop ( $I_i$ - $I_{ii}$  were used as the current leads and  $U_i$ - $U_{ii}$  as the potential leads), with the radiation of  $f=2.043$  GHz and without the radiation at  $T=0.35$  K.

at  $H=160$  G. The sample geometry is shown in the inset of Fig. 3. The NS contact resistance in this sample was also  $1\text{--}2\Omega$ . A similar anomalous proximity effect has been discussed recently in Ref. 6. The corrections to the resistance had positive and negative signs there.

It is evident from the experimental data that the anomalous behavior is not a simple shunt of the normal resistance by a superconducting part. First, we observed the increase of the resistance below  $T_C$  in some samples, while the shunt model for particular system can only lead to a decrease. Furthermore, if the steplike transition is a superconducting transition of the suffocated aluminum shunt [one can see from Fig. 2(a) that  $H_C$  of aluminum film is  $\sim 240$  G, while the step takes place near  $H=130$  G] then one would expect the features in the magnetoresistance curve measured across the loop near  $H=130$  G, curve (i)&(ii) of Fig. 2(a). In fact no features are observed at this field. Finally a simple estimation of the possible shunt effect for the sample with the first geometry gives a value which is 1 order smaller than that observed.

Increasing the temperature from 0.35 to 0.95 K reduced the amplitude of oscillations in the type (i) wire and shifted the step to lower fields, see Fig. 2(b). The temperature dependence of the amplitude of the first oscillation is given in the inset of Fig. 2(b) (the choice of the amplitude of the first oscillation as a characteristic of the effect will be clarified in the following discussion). Relative to its value at  $T=0.35$  K

the amplitude is reduced to about  $1/2$  at  $T=0.95$  K. At the same time the amplitude of the steplike transition did not reveal any pronounced changes.

To obtain more information the magnetoresistance measurements have been repeated under rf irradiation. We used frequencies of 2.04 and 9.86 GHz, where the coupling of rf radiation to the samples was the most effective. The effects at both frequencies were similar. In the wire of type (ii) geometry the rf radiation suppressed correction to the resistance in a gradual manner with increasing rf power. At a high-radiation power the correction was totally suppressed. In the type (i) wire the rf radiation suppressed only the oscillating part of the magnetoresistance curve, leaving the steplike transition unaffected, see Fig. 4(a). We found that the aluminum film itself was sensitive to the radiation, Fig. 4(b). The nonlinearity in the  $I$ - $V$  curve determined by the superconducting aluminum film disappeared under rf irradiation. We note that the photon energy,  $\sim 4 \mu\text{eV}$ , is much smaller than the superconducting gap,  $100\text{--}200 \mu\text{eV}$ , hence a direct excitation of quasiparticles by rf quanta is not possible. On the other hand, the temperature of the sample did not change, because the position of the step in the magnetoresistance curve under irradiation remained the same [compare with the Fig. 2(b)]. Consequently, thermal suppression of the order parameter is also excluded.

The rf experiments with the samples of second geometry depicted in Fig. 3 gave qualitatively the same results. The radiation suppressed a smooth type of correction, leaving the steplike transition unchanged. We did not find rigid relations for the anomalous corrections with the sample geometry, the parameters of materials or the fabrication processes. In total 17 samples have been measured, and eight of them had the steplike features. In this paper we present the data of just two samples, which are most representative.

## DISCUSSION

The experimental data indicate that there are at least two mechanisms by which a superconductor can influence the resistance of a normal wire. They differ from each other in sensitivity to temperature, magnetic field, and rf irradiation. We argue that the smooth type of corrections observed in our samples should be attributed to the classical “proximity” effect. Below  $T_C$  the aluminum induces in the silver a condensate function, which changes the density of states and distribution function of the quasiparticles. Two mechanisms work in opposite directions: the effect of decreasing the density of states increases the resistance, while that of distribution function decreases the resistance. In most cases the resulting effect has a negative sign, so that the resistance decreases. A penetration length for the condensate function is determined by the phase-breaking length of the normal metal,  $L_\varphi$ . The amplitude of the effect depends on the ratio of the normal resistance to the NS barrier resistance  $r=R_N/R_b$ , and the relationship between the Thouless energy,  $E_{\text{Th}}=\hbar D/L^2$ , the thermal energy,  $E_T=k_B T$ , and the bias voltage energy,  $E_V=eV$ , where  $L$  is the length of the normal wire,  $D$  is the diffusion constant. The amplitude of the effect has a maximum value when these energies are comparable. The magnetic field gradually suppresses the condensate function, and hence the correction to the resis-

tance, by increasing the effective phase-breaking rate. In the type (i) structure the magnetic field additionally produces a phase difference between the aluminum banks of the loop separated by the silver branch,  $\varphi = 2\pi S_{\text{loop}}H/\Phi_0$ , which results in a periodic modulation of the condensate value and magnetoresistance oscillations. In the type (ii) structures the phase difference across the silver film beneath the aluminum at the overlapping region is too small to modulate the induced condensate and produce the oscillations.<sup>7</sup>

Following the method described in Ref. 1 we derived an analytical formula for the classical “proximity” correction in the type (i) wire:

$$\Delta R \approx -\frac{Rr^2}{32k_B T} \int d\epsilon F'(\epsilon, V) \{ |b|^2 [(\sinh[2\theta']/2\theta' - \sin[2\theta''/2\theta''] - \text{Re}b^2(\sinh[2\theta]/2\theta - 1)) \} \\ \times (1 + a \cos[\varphi]).$$

Here

$$F'(\epsilon, V) = (\cosh^{-2}[(\epsilon - eV)/\kappa_B T] + \cosh^{-2}[(\epsilon + eV)/\kappa_B T])/2,$$

$$b = (\theta M)^{-1},$$

$$M = 2 \cosh \theta (\cosh[2\theta] + \sinh^2 \theta)$$

$$+ \sinh \theta (\sinh[2\theta] + \cosh \theta \sinh \theta),$$

$\theta$  is defined as

$$\theta = \theta' + i\theta'' = [L_\varphi^{-2}(H) + i2\epsilon/hD]^{1/2}L/2,$$

$$L_\varphi^{-2} = L_\varphi^{-2} + (2\pi w H/\Phi_0)^2$$

and  $w$  is the width of the silver wire. The empirical factor  $a$  has been introduced to account for the nonoscillating part of the corrections caused by the finite width of the silver films. We subtracted the magnetoresistance curves with and without the radiation in Fig. 4(a), and approximated the resulting curve using  $r$ ,  $w$ , and  $a$  as the fitting parameters. The approximation is plotted as the curve with open circles in Fig. 4(a). It gave reasonable values for  $r \sim 1.7$  and  $a \sim 0.6$ , but gave a rather small value for  $w \sim 0.04 \mu\text{m}$ . Using these parameters we calculated the amplitude of first oscillation at different temperatures and plotted the theoretical curve together with the experimental data in the inset of Fig. 2(b). In the calculations we assumed  $L_\varphi$  to be temperature independent. One can see a rather good agreement between theory and experiment.

Although the classical proximity theory gives a good description of the smooth-type correction to the resistance, it cannot account for the anomalous correction. On the one hand, the proximity theory is able to explain the amplitude of the effect, and even the positive sign of the correction in some samples. Indeed there are some special cases, when the effect of decreasing the density of states near the NS boundary exceeds that of the change in the distribution function, so the resulting effect should have a positive sign.<sup>8</sup> It is highly possible that in some mesoscopic structures this situation has been realized. The sharp transition in the magnetic field can then be attributed to the appearance of the vortex near the NS boundary which suppresses the order parameter of the superconductor. On the other hand, there was no pronounced temperature dependence of the step amplitude in the temperature range from 0.35 to 0.95 K, while theory predicts at least  $T^{-1}$  dependence [the amplitude of the magnetoresistance oscillations in the same sample exhibited a noticeable growth, see Fig. 2(b)]. Also the appearance of the vortex should change not only the amplitude of order parameter, but also its phase, and one would expect a slip of the oscillation phase in the curve in Fig. 2(a). In fact the oscillations preserved their phase after the step transition.

Experiments with rf irradiation can help to clarify the issue. In these experiments the magnetoresistance oscillations disappeared, when rf radiation was applied to the sample. The effect can be explained with the proximity theory. Under irradiation the phase  $\varphi$  becomes a function of time,  $\varphi = \varphi(H) + 2eV_\omega/(\hbar\omega)\cos[\omega t]$ , where  $\varphi(H)$  is the magnetic-field-dependent part of the phase,  $\omega$  and  $V_\omega$  are, respectively, the frequency and the amplitude of the radiation. The situation is analogous to the case of the dc Josephson critical current under rf power. To find the amplitude of the proximity effect one should make a time average of the equation for  $\Delta R$ . One can then obtain a formula where  $\cos[\varphi]$  has been replaced by  $J_0[2eV_\omega/\hbar\omega]\cos[\varphi(H)]$ , and  $J_0$  is the zero-order Bessel function. Hence the proximity effect should be suppressed with increasing rf power. The absence of a nonmonotonous behavior of  $\Delta R$  with  $V_\omega$  in the experiment can be attributed to the smearing caused by thermal fluctuations. At the same time the steplike transition was not changed under irradiation, demonstrating that it is not related to the classical proximity effect. The effect of rf irradiation on the superconductor itself which resulted in the linearization of the  $I$ - $V$  curve across the loop, see Fig. 4, was not studied in detail in this work. We can only suppose that it is connected with the development of phase-slipping centers in mesoscopic superconductors under irradiation.

An explanation of the anomalous correction may come from the theory recently suggested by Nazarov and Stoof.<sup>9</sup> It was shown that in materials with a nonzero electron-electron interaction constant, the induced condensate produces a weak pair potential which serves as a source for the Andreev scattering throughout the normal conductor. As a result the resistance of the normal conductor changes. The correction to the resistance can be either positive or negative depending upon the sign of the interaction constant. In the case of silver metal, this can reach a few percents of the normal resistance. There are still some difficulties in the direct application of this theory to the experiments. First of all, to explain an opposite sign for the effect in different samples one should

allow for the fact that the electron-electron interaction constant can vary in ultrasmall structures produced from the same material. Furthermore, the theory does not shed light on the mechanism for the steplike transition in a magnetic field. Finally, the theory has been derived in the limit of very low temperatures,  $E_{\text{Th}} \ll E_T$ , while in our experiments the thermal and Thouless energies were comparable and we should expect a suppression of the effect.

In conclusion we studied the corrections to the conductance caused by the superconductor in normal mesoscopic metal structures. We observed an anomalous type correction, which cannot be explained within the framework of the classical “proximity” theory. They differ from the usual “prox-

imity” corrections in temperature dependence, sensitivity to magnetic field and rf irradiation. The nature of the effect is still unclear and further theoretical efforts are needed to solve the problem.

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